EVOLUTION OF SOLID-STATE INDUCTION MODULATORS FOR A HEAVY-ION RECIRCULATOR

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Background

The Laser Program at Lawrence Livermore National Laboratory (LLNL) pioneered the use of large-scale glass lasers to heat inertial-fusion targets. Today, that same exploratory spirit applies to our latest laser-fusion effort—the National Ignition Facility (NIF). The NIF has the potential to pave the way to commercial power extraction from inertial fusion, as long as the generating system is affordable and it operates repetitively. These fundamental issues of cost and repetition rate have stimulated a search for alternative fusion-target drivers to replace large, single-shot lasers. We are developing an ion approach whereby converging beams of heavy ions act as the driver. Like lasers, the ions impart their energy to the target and produce fusion temperatures. The difference lies in the ability of particle accelerators to generate repetitive bursts of ions with a higher efficiency at a lower cost.

Several accelerator concepts are being investigated for Inertial Fusion Energy (IFE).[1] The challenge is to identify an accelerator configuration that meets the technical requirements for heavy-ion fusion (HIF) and competes economically with existing and alternate energy sources. To meet the challenge, the LLNL HIF project is investigating a circular induction accelerator called a recirculator,[2] as shown in Fig. 1. The recirculator is economically attractive because the beam acceleration sequence uses the most expensive accelerator components multiple times. However, the recirculator concept presents some unique technical challenges, because the sub-relativistic ion completes a circulation in a short time and is constantly gaining speed with each lap. Consequently, the pulsed modulators that accelerate and shape the beam must produce uniquely tailored pulses at repetition rates that are continuously variable and that can exceed 100 kHz. Therefore, our role in the HIF project is to investigate and to develop agile induction modulators that use the latest in solid-state power technologies.

Development Overview

Our efforts to develop agile induction modulators are guided by the future experimental needs of the HIF project. In close collaboration with Lawrence Berkeley Laboratory (LBL), we are developing a short-term and a longer-range experimental capability that will be shared between the two laboratories. The short-term experiment is a small-scale recirculator (4.5-m-diam ring), presently being built at LLNL, that will be the first demonstration of the recirculator concept. The longer-range experiment is a much larger scale recirculator (30-m-diam ring) that will be built using the proposed Induction Linac Systems Experiments (ILSE) accelerator at LBL as the heavy-ion source. Both of these experimental activities require significant advancements in the technology for induction-accelerator modulators.

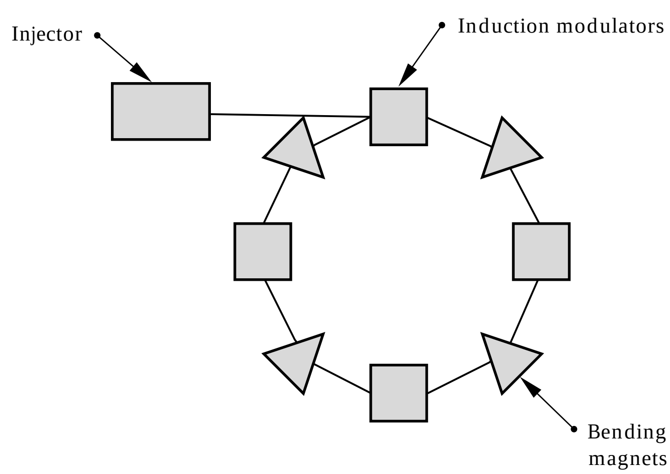

FIGURE 1. The recirculator uses a multipass acceleration concept to reduce system costs. (30-00-0295-0486pb01)

For our initial experiments, we selected a full-scale demonstration of solid-state power management based on the long-range requirements of the proposed LBL recirculator. A prototype modulator was built and tested that achieved the nominal parameters of 5-kV, 200-A pulses that vary in format from 1 µs to 400 ns and repeat at a 50- to 150-kHz repetition rate.

In addition to pulse-width and repetition-rate agility, the induction cell modulators for a recirculator will ultimately incorporate a much more sophisticated power-management scheme. The amplitude and shape of each individual acceleration pulse must be tailored to accurately match the continually changing velocity and shape of the ion beam. This will require the implementation of feedback control capabilities to the basic modulator technology. At LLNL, we are presently developing an induction modulator for our short-term experimental needs on the small-scale recirculator. This new modulator will generate precisely programmed waveshapes in addition to pulse-width and repetition-rate agility. While the total peak power requirements are much smaller in this second developmental modulator (600-V, 100-A pulses), it must still operate in excess of 100 kHz while delivering a sequence of pulses that have a precisely controlled shape and amplitude.

This article describes the requirements, designs, and results from our initial work, which focused on the larger modulator technology for the LBL recirculator experiment, followed by our present efforts to develop a "smarter" modulator technology. We also summarize spin-off applications of the HIF induction technology currently being developed.

Solid-State Induction Technology

Induction machines accelerate the beam through electrical cavities that apply the accelerating voltage to the beam. These cavities contain toroids of ferromagnetic material that encircle the beam axis and enable the applied accelerating voltage to be impressed along the beam while the outer cavity surfaces remain at ground potential.[3] Figure 2 illustrates the differences between a linear induction accelerator and a recirculating induction accelerator. Figure 2(a) shows a linear arrangement of induction cells, where each cell receives fixed duration pulses of a relatively low pulse repetition frequency (prf).[4] Figure 2(b) is a circular arrangement of the induction cells, but the pulse parameters for these cells differ greatly from their linear accelerator counterpart:

- Recirculators operate in a rapid burst of multiple pulses, corresponding to the number of beam circulations in the ring.
- The pulse separation changes during the burst because the ion beam gains speed from each preceding pulse.
- The pulse width changes during the burst because the beam is spatially compressed as it gains speed.
- The prf within the burst is very high (10–150 kHz) because the beam accelerates on each lap around the ring.

The need for complex pulse agility led us to examine solid-state switching components that have an on / off capability. The intrinsic speed of solid-state switching satisfies our high prf requirements, while the on / off switching action of some semiconductor devices enables us to select an arbitrary pulse width. Eventually, we selected field effect transistors (FETs) as the preferred switching elements because they have fast rise and fall times, low gate-drive power, low on-state impedance, and a capacity for high-prf operation.

The basic concept of our solid-state modulator is simple—close the FET switches to connect a large capacitor bank to the accelerator induction cell and open the switches when the pulse is long enough. However,

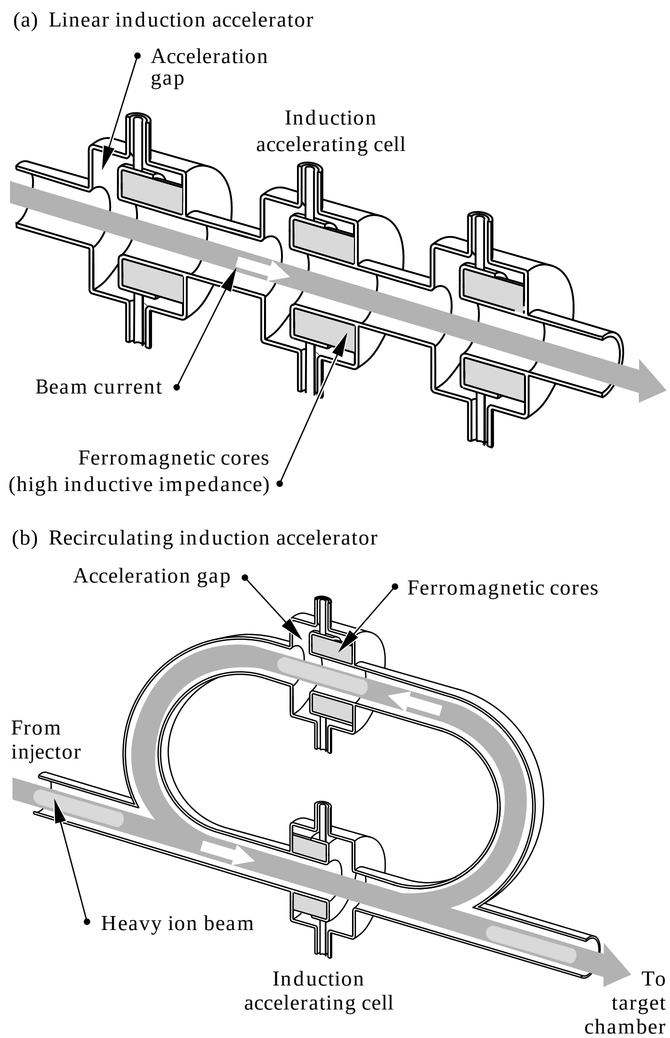

FIGURE 2. Ferromagnetic cores are used in induction cells to accelerate the beams. (99-74-0491-0659pb01)

this action becomes considerably more complicated due to the inductive nature and magnetic properties of the accelerator core: (1) The inductance of the accelerator cell is energized by the applied pulse. When the FET switches are commanded to open, the cell inductance generates a very large voltage in an attempt to maintain a constant current. (2) The applied pulse also magnetizes the core material and leaves it in a different state of polarization following the pulse. The difficulty lies in resetting the core to its former magnetic state in the short time between pulses. We resolved these difficulties by applying the circuit architecture shown in Fig. 3.

When the switch S1 is closed, the energy storage capacitor C1 is connected directly across the induction cell L1. The voltage VC1 accelerates the ion beam, but it also drives a steadily increasing magnetization current in the cell [Fig. 3(b)]. Once the acceleration pulse has ended, S1 opens and the cell current begins to decrease. The sudden change in cell current results in a rapid voltage reversal on L1, which continues in the positive direction until the diode D1 is forward biased. At that time, the cell current is fully diverted from the switch branch to the reset capacitor C2. The reset capacitor is precharged to the voltage VC2, which dictates the rate of cell current decay and helps to restore the magnetic flux density back to its original value. When the cell current reaches zero, D1 turns off and the pulse is ended; however, the core reset action is still incomplete. Additional reset is provided by reversing the flow of cell current. Energy for the current reversal is stored in the FET snubber capacitors (not shown) and reinforced by current from the external charging system. The diversion of cell current to C2 causes VC2 to increase with each pulse and results in a net accumulation of voltage during an acceleration sequence. However, the capacitance value of C2 is equal to or greater than C1, so the net voltage increase is very small. The regulator element in Fig. 3(a) maintains VC2 at a steady-state value by returning the recovered energy back to C1 at the end of each acceleration sequence. Note that C1 contains far more energy than the ion beam and core material need per pulse, so C1 does not require recharging during a burst.

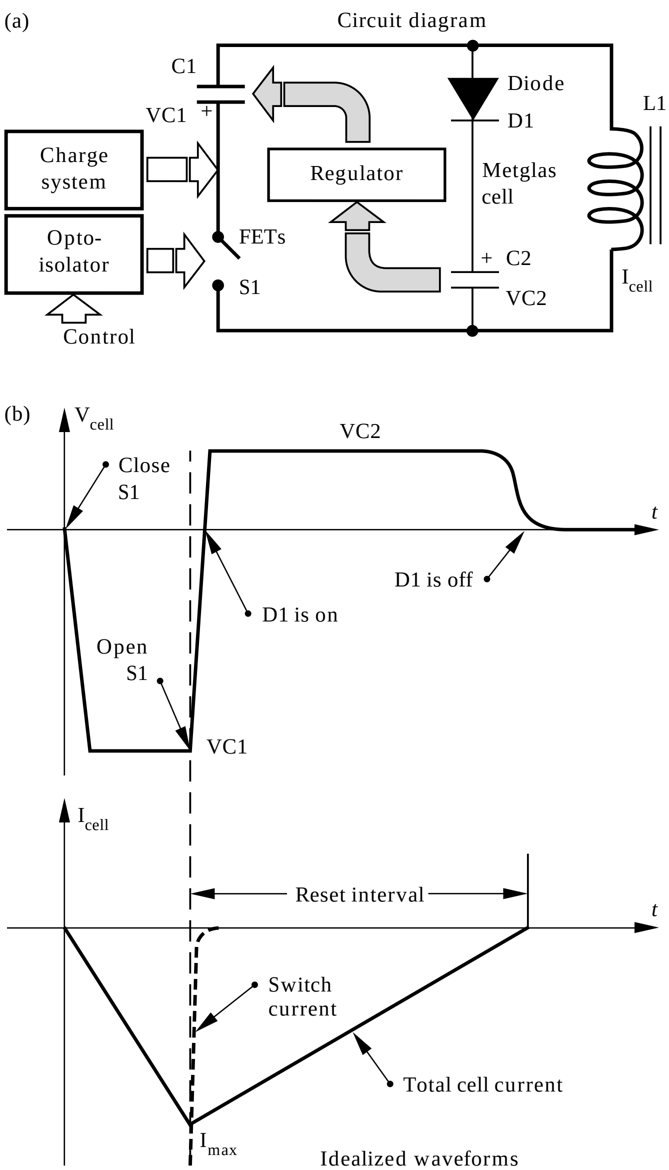

FIGURE 3. (a) Circuit that provides core drive and reset functions for a single induction cell. (b) Waveforms that illustrate the operation of the circuit shown in (a). In (b), t = time. (30-00-0295-0487pb01)

ILSE-Scale Induction Modulator

Our first attempt to implement the circuit architecture of Fig. 3 resulted in a 4-kV modulator and cell switched by a total of 24 FETs.[5] Our latest HIF machine features a larger switching system, containing a total of 128 FETs. Figure 4 shows the physical layout of four parallel 1-kV

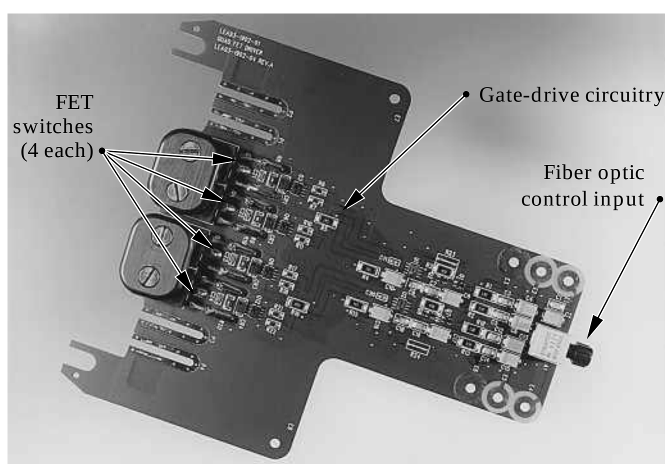

FIGURE 4. Photograph of a circuit board containing FET switches and optically controlled drive circuitry. (30-00-0295-0489pb01)

power FETs on each of 32 circuit boards along with the two isolated gate-drive circuits that control them. The on / off commands to each gate drive are delivered through a single optical fiber. Isolated control power is supplied from a dc / dc converter for each circuit board. The 32 circuit boards are divided into four modules each containing a stack of eight series-connected boards. The four modules and their capacitor banks surround a single induction cell, as shown in Fig. 5.

FIGURE 5. Photograph illustrating the close integration between the FET switching modules and the induction core. (30-00-0295-0490pb01)

Space is available to expand this modulator to a total of 8 modules, doubling its peak power capability from 4 MW to 8 MW.

Figures 6 and 7 contain preliminary performance data for 3-kV operation. Figure 6(a) shows cell voltage and the switch voltage on module 4 for a 1-µs pulse. Figure 6(b) shows currents from modules 3 and 4, indicating a good current balance between them. Each module has two current probes so that eight probe signals are needed to show the total machine current. The general ramp-like shape of the current waveform is characteristic of an inductive load with a constant applied voltage. The narrow pulse at the start of the

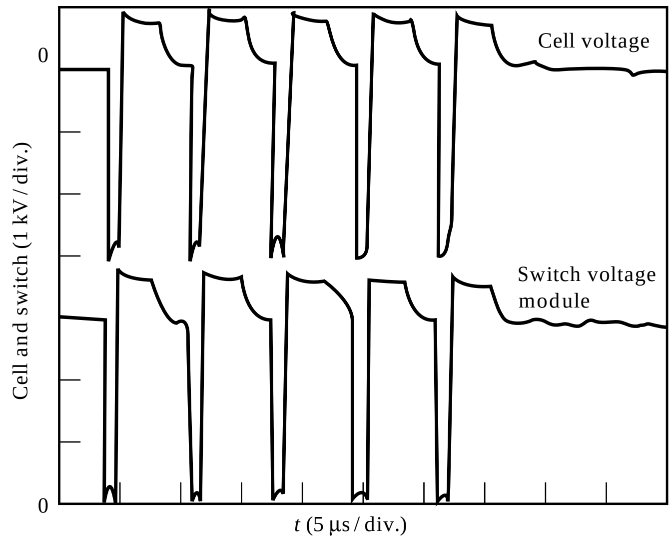

FIGURE 7. Five-pulse burst at 3 kV showing a 150-kHz pulse rate. (30-00-0295-0492pb01)

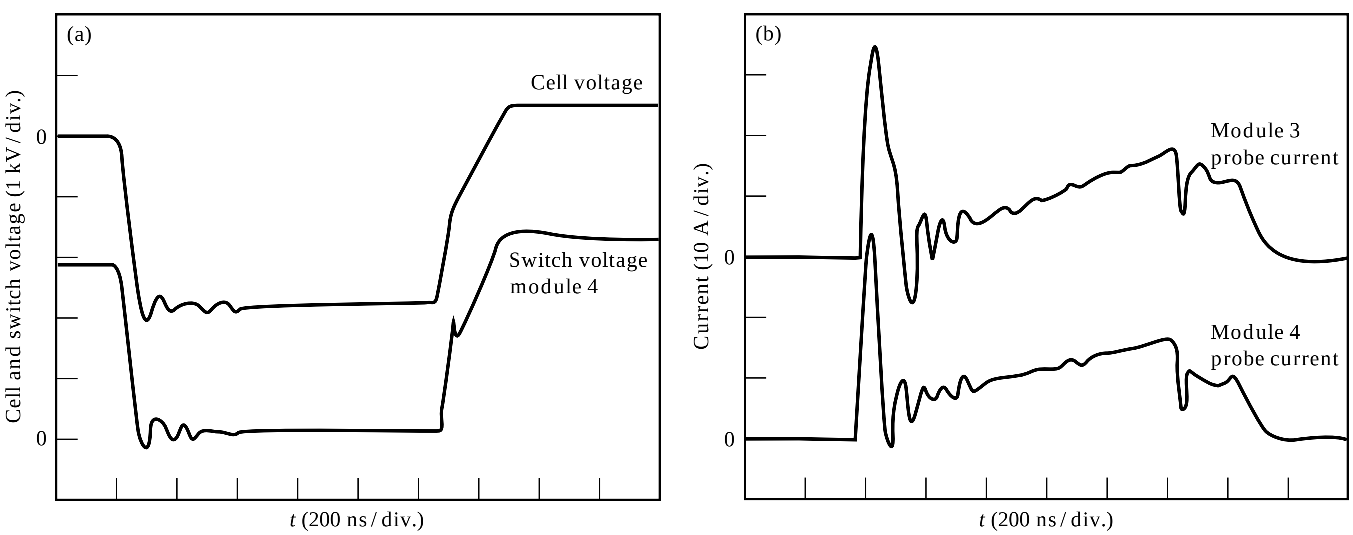

FIGURE 6. (a) Cell and switch voltages for a 3-kV charge voltage and a 400-V reset voltage. Waveforms are the acceleration portion of the whole voltage waveform. (b) Switch currents from modules three and four showing a 15-A peak current at the end of a 1-µs ramp. Peak cell current is the sum of all module currents (= 120 A in this case). (30-00-0295-0491pb02)

current signal is due to the discharge of external cable capacitance. Figure 7 shows the cell and switch voltage of module 4 during a 5-pulse burst at a 150-kHz rate. The machine has achieved full voltage operation at 5 kV, but much work still remains in modeling the system and understanding the behavior of the magnetic core during the burst.

Small-Scale Induction Modulator

The small LLNL recirculator, currently under construction, consists of 32 accelerator stations spaced around a 4.5-m-diam ring. Each accelerator station houses a 600-V induction modulator and cell. When a stream of low-energy ions are injected into the ring, they are steered into a circular path by an arrangement of electrostatic dipoles. As the singly charged ion stream passes by each induction cell, the particles undergo a nominal 500-eV gain in energy. The ions complete 15 revolutions in the recirculator before being extracted.

The transport scenario described is further complicated by the large space charge of the ion bunch. To inhibit ion scattering, the recirculator must provide confinement forces that bind the beam in the radial and axial directions. The electrostatic quadrupoles provide the radial restoration, but the axial spread is controlled by shaping the acceleration pulse so that the space charge forces are balanced by the accelerating voltages. Basically, the ions in the lead receive less acceleration (lower mean voltage) than the trailing ions that receive additional acceleration (higher mean voltage). In practice, the pulse shape is generated by adding a 500-V rectangular pulse with two triangle-shaped "ear" pulses at the leading and trailing edges. The leading-edge ears have a negative polarity to decelerate the head of the beam, while the trailing-edge ears have a positive polarity to speed up the tail. There are several possible combinations of pulses that form an "acceleration schedule" that may be used to accelerate the ion beam. Figure 8(a) shows one example, which details the schedule of acceleration pulses, and Fig. 8(b) shows the ear-pulse schedule. As the ion beam is bunched together, the acceleration pulses grow narrow and the ears become taller to restrain a spatially compressed beam. Figure 9 shows the ensemble of net accelerating voltages from start to finish.

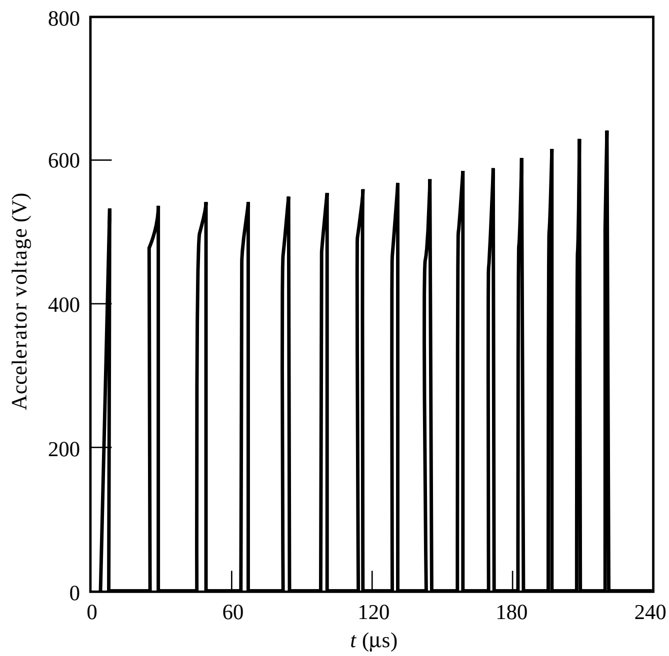

FIGURE 9. This voltage waveform, which appears in the accelerating gap, is the summation of the accelerator and ear pulses shown in Fig. 8. (30-00-0295-0494pb01)

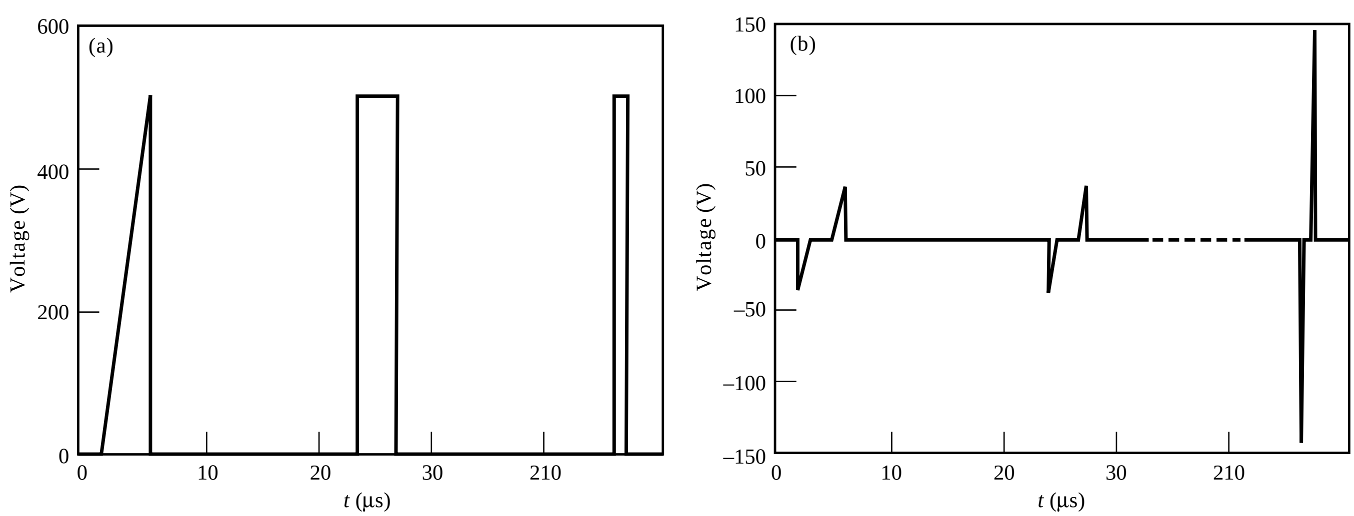

FIGURE 8. (a) Accelerator pulses vary from a 4-μs rise-time ramp to a 1-μs rectangular pulse. Interpulse spacing starts at 17 μs and reduces to 10 μs. (b) These ear pulses are added to the acceleration pulses to provide longitudinal confinement of the ion beam. (30-00-0295-0493pb02)

Generating the pulse format shown in Fig. 9 is the responsibility of our "smart" induction modulator. In this case, FETs are still used to connect a precharged capacitor bank to an induction cell, but the smart feature of this new modulator lies in the use of the FETs as amplifier elements instead of on / off switches. In addition, our new modulator and cell use two separate induction cores, one for the main accelerator pulse and one for the ear pulses, to generate the net voltages of Fig. 9. Figure 10 is a block diagram that illustrates the nesting of two cores and two modulator circuits. Fast feedback amplifiers are used to control two power FET arrays so that each core voltage is a scaled version of an applied input waveform. A computer system is used to command two programmable waveform generators to produce a properly shaped pulse train. The ear core in Fig. 10 is made from PE-11B ferrite while the main accelerator cores are an assembly of three 2605S-3A Metglas[6] cores.

The modulator and core assembly are still in the design phase, but comprehensive modeling of the electronic portion of the design is presently underway. We are using the Micro-Cap IV[7] circuit analysis program to model the cell and power amplification circuits. Figure 11 is a typical simulation showing an input waveform compared with the output voltage at the accelerator cell.

Spin-Off Technologies

The various power-control technologies being developed for HIF are also applicable in other programs. For example, the Advanced Radiographic Machine (ARM), a multipulse electron-beam accelerator for dense-target tomography, derives its power system from the HIF work, but requires a peak power and repetition rate far beyond those needed for heavy-ion recirculators. The ARM induction modulator is designed to generate 15-kV pulses that vary in width from 200 ns to 1 μs at repetition rates up to 1 MHz.[8]

We also applied our HIF knowledge to two other projects. During FY 1992, we built and tested a miniature induction modulator as a power source for pulsed plasma processing.[9] This work was based on the proposition that plasma processing is a dynamic electrochemical reaction that also requires an agile power source to help maintain an optimal process efficiency. During FY 1994, we applied our FET switching experience to the design and construction of a compact power source for a solid state laser array.[10,11] In this case, the work focused on enhancing the industrial and medical uses of the laser array by reducing the size and cost of the power system.

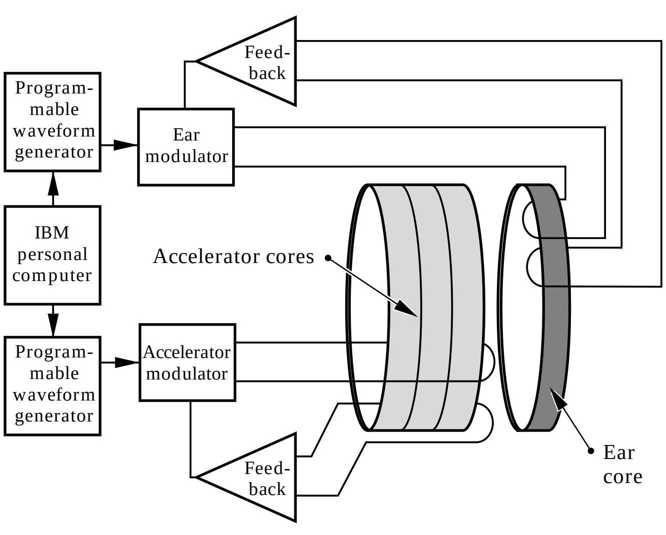

FIGURE 10. The gap voltage is generated by two separate core and modulator circuits. (30-00-0295-0495pb02)

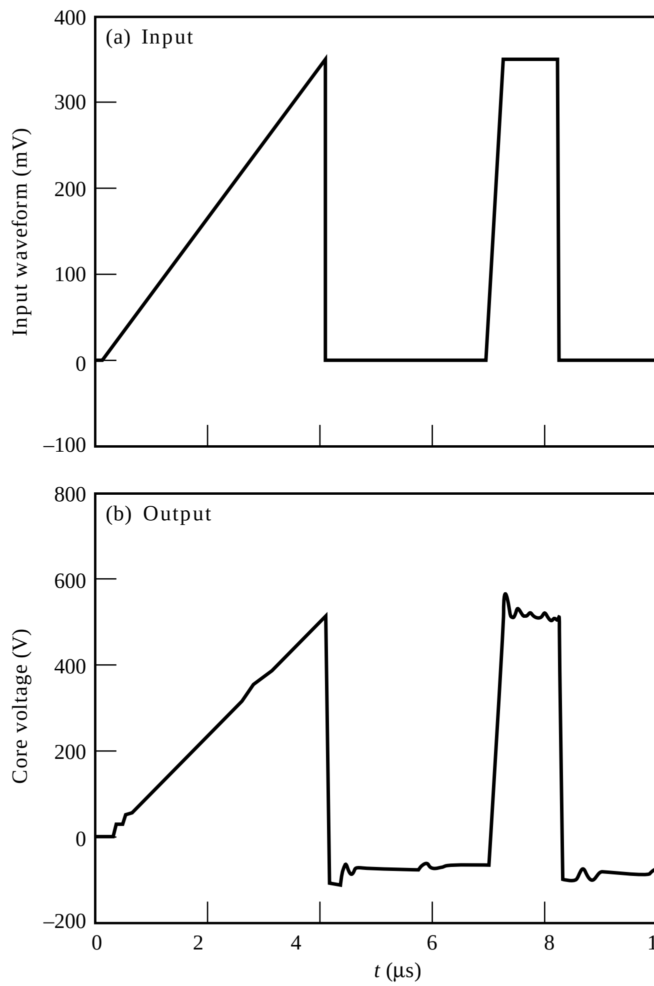

FIGURE 11. Circuit simulation showing two examples of (a) input voltage waveforms and (b) amplified voltages at the cell. The negative bias on the amplified voltage signal is the result of the applied reset voltage. These simulations contain detailed amplifier models that are used to guide our design. (30-00-0295-0496pb01)

Summary

Induction accelerators are typically powered by energy stored in a pulse-forming network that delivers an accelerating pulse of a fixed duration and amplitude. This type of accelerator system is limited in prf to a few kilohertz and treats the dynamic beam as a simple time-invariant load. Our research has merged the growing capability of solid-state power control with induction accelerator technology to produce a new accelerator system that is fast, flexible, and interactive with the beam. As a result, the beam may receive variations in pulse shape, amplitude, width, and prf to suit a specific objective in beam quality or accelerator performance. The solid-state powered accelerator delivers intelligent beam power that is actively directed in the right proportions at the right time. The recirculator is only one example of how smart power management can improve the capability of well-established technologies.

Notes and References

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